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Origin of large albedo ^{3}He/^{4}He ratio

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Abstract. The Alpha Magnetic Spectrometer (AMS) has observed cosmic ray helium below the geomagnetic cut-off with a large fraction of ^{3}He. We have examined the spallation process by which cosmic ray nuclei interact with air nuclei and fragments into ^{3}He. This process may explain a few ^{3}He observed above 500 MeV/n near $|\lambda_{\rm m}|$ = 0.6. The estimated energy spectrum of ^{3}He from the pick-up process, in which proton interacting with ^{4}He gives rise to ^{3}He and D, is too steep compared with the observed spectrum. We also examined the disintegration of air nuclei during high energy collision which produces of ^{3}He. As in the pick-up process, it is required that the projectiles should be the observed secondary protons, which have the same latitude dependence. However, the lack of interaction cross-section prevent detail simulation.

1 Introduction

Cosmic light isotopes such as ^{3}He play an important role in determining the mean amount of matter that cosmic rays traversed inside the galaxy. The cosmic ray flux ratio $^3\mathrm{He}/^4\mathrm{He}$ is approximately 10%, much higher than the primordial abundance $^3\mathrm{He}/^4\mathrm{He} \sim 10^{-4}$. The excess of ^{3}He comes from the spallation of cosmic ^{4}He interacting with interstellar medium (ISM). ^{4}He lose one nucleon and become ^{3}T or ^{3}He. The ^{3}T half life is 12.26 year, much smaller than 10^7 years, the typical residence time of cosmic rays. So the ^{3}T almost completely decay to ^{3}He.

An estimation of the ^{3}He produced in the atmosphere provides the tool to correct for atmospheric contamination in balloon borne experiments and to eliminate some uncertainties in the calculations of cosmic ray transportation and cosmogenic nuclei (Papini et al. , 1993).

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^{3}He below the geomagnetic rigidity cutoff had been observed in radiation belts (Chen et al. , 1994). The $^3\mathrm{He}/^4\mathrm{He}$ depends on the energy and the L shell number. At kinetic energy 40 - 100MeV/n, the $^3\mathrm{He}/^4\mathrm{He} = 8.7 \pm 3.1$ at L=1.1-1.5 and $= 2.4 \pm 0.6$ at L=1.5-2.3. It was suggested that protons in radiation belts with energy E≥200MeV interact with ambient helium at altitude 4200-7000km and produce $^3\mathrm{He}/^4\mathrm{He} \simeq 2$, which explain the ratio at L=1.9. For L~ 1.2, fragmentation of ambient oxygen may contribute to the $^3\mathrm{He}/^4\mathrm{He} \simeq 6$. However, the secondary spectra of ^{3}He and ^{4}He cannot be reproduced.

Light isotopes, including ^{3}He in the energy range of 10-20 MeV/n, in the radiation belts are also detected by SAMPEX (Cumming et al. , 1995). Selesnick and Mewalt (1996) studied the production of light isotopes and compared with the measurements from SAMPEX. The major source of ^{3}He production is atmospheric oxygen at L=1.2. At higher L, the ^{3}He is mostly produced by ambient helium. Very little ^{3}He is produced from atmospheric oxygen and it concentrates near the edge of loss cones.

In June 1998, the Alpha Magnetic Spectrometer (AMS) (Alcaraz et al. , 1999) performed an test flight aboard the space shuttle. It was found that the primary cosmic helium contains approximately 11.5% of ^{3}He (Alcaraz et al. , 2001). Helium with rigidity below the geomagnetic rigidity cutoff was also observed; 90% of it is ^{3}He, or $^3\mathrm{He}/^4\mathrm{He} = 9$. These ^{3}He events are found in low altitude (~ 380 km) and magnetic latitude $|\lambda_m| < 0.6$ rad. Their energies range between 100 to 1200 MeV/n, higher than the two measurements mentioned above. The trajectory of the events detected by the AMS are calculated by a trajectory tracing program (Huang et al. , 2001). These events are found to originate from the atmosphere and sink to the atmosphere in a very short time, in the order of bounce period or drift period. This paper investigated three processes which could contribute to the AMS high energy ^{3}He observed by the AMS.

2 Spallation of cosmic helium

Cosmic ray ^{4}He nuclei interact with air nuclei, they break up into ^{3}He, whose rigidity would be $^3/_4$times that of ^{4}He. When the incoming ^{4}He coming from the west has rigidity less than about $^4/_3$times the cut-off rigidity in that direction, the ^{3}He fragment, having rigidity smaller than the cut-off turns into as an albedo. Owing to the geomagnetic field, it return back to the atmosphere at a mirror latitude along the field line. Heavier cosmic ray nuclei would also produce both ^{4}He and ^{3}He by the same process. But ^{4}He would continue to move in the same direction as the incoming nucleus due to its rigidity being similar to that of the parent nucleus. Based on the equivalent number of helium nuclei in the heavier component of cosmic rays, it is expected that nuclei of charge ≥ 3 would contribute about 2.25 times that by helium component (Papini et al. , 1996). In order to estimate the spectra of ^{3}He and ^{4}He, one has to carry out the trajectory calculations by incorporating both interaction and energy loss of both primary and secondary particles. These spectra should have a low energy cut-off depending mainly upon the latitude.

The main ingredient in this estimate is the cross-section for interaction of ^{4}He and heavy nuclei with air, in which the projectile breaks up and produces the ^{3}He. Since we are interested in $|\lambda_m| < 0.6$, where λ_m is the magnetic latitude, the cross-section is expected to be independent of energy. At these energies, some measurements give values around 550 mb, while others give about 440 mb. The former includes the nuclear excitation of both the projectile and target nuclei without the break-up of the projectile. Therefore, we modified the empirical relation given by Stephens (1997) as

$$\sigma_{P,T} = 60(kA_P^{1/3} + 1.03A_T^{1/3} - 1.25)^2 \text{ mb} \quad (1)$$

where P and T denote the projectile and target respectively; and k = 1 and 1.04 for ^{4}He and ^{3}He, respectively. The branching ratio for the production of ^{3}He by the interaction of ^{4}He is 0.123. In the case of heavier projectile, the value of k is taken to be same as that of ^{4}He and it is reasonable to scale the above parameter by an equivalent number of ^{4}He in a nucleus of mass number $\mathrm{A_P}$.

2.1 Simulation

Compared with the amount of matter traversed by cosmic rays in ISM, there are plenty of materials for spallation in the atmosphere. At altitude 40 km above the Earth surface, the depth is approximately $100\mathrm{gm/cm}^2$ along a horizontal direction. Some ^{3}He might be produced by the spallation reaction.

We made use of the cosmic helium spectrum (Alcaraz et al. , 2001) and modulated it by the geomagnetic rigidity cutoff, assuming that all the ^{3}He follows the direction of the parent ^{4}He. In order that the ^{3}He rebounds to space, only the primary cosmic helium coming from the western hemisphere between zenith angle $80°$ to $90°$ is considered. Cosmic rays from the east would be bent toward the Earth and are less likely to rebound to space. In this calculation, ^{3}He is produced at 40 km altitude, the same condition as un AMS (Huang et al. , 2001), and then transported to the AMS altitude along the same L shell.

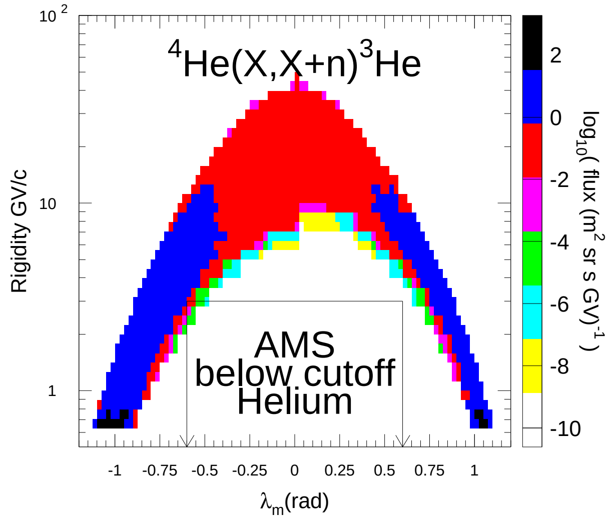

Fig. 1. The distribution of ^{3}He produced by $^4\mathrm{He(X, X+n)}^3$He, where X is atmospheric nucleus. Only few events at the top left corner of the AMS below cutoff ^{3}He can be explained by this interaction.

2.2 Results and discussions

The results from this simple calculation show that ^{3}He produced by spallation exists only in specific phase space of rigidity and magnetic latitude, as shown in Fig. 1. Only few events near $-0.6 < \lambda_m < -0.5$ and energy >1 GeV/n can be explained by this mechanism. Even if we consider the energy loss, there is no contribution from ^{4}He through this process below 900 MeV/n. In this respect, heavy cosmic ray nuclei play an important role because they slow down faster than ^{4}He before they interact in the atmosphere. In one interaction length, the energy loss of ^{4}He is about 100 MeV/n, while for O and Fe it is 225 and 375 MeV/n, respectively. Thus, at $|\lambda_m| = 0.6$, Fe can produce 550 MeV/n ^{3}He compared to 900 MeV/n by ^{4}He. However, even Fe cannot account for the observed ^{3}He at low latitude due to the higher geomagnetic cut-off for the primary cosmic rays.

^{3}T is produced by a similar process, $^4\mathrm{He(X, X+p)}^3$T. The ^{3}T produced carries one charge and $^3/_4$of the original momentum, the rigidity becomes $^3/_2$of the original rigidity. Therefore it will show up above the cutoff. This ^{3}T hardly decays while traveling near the Earth and could be detected by the AMS. Since the cosmic ray ^{3}T is almost negligible, the amount of ^{3}T can be used to estimate the ^{3}He produced by spallation. If some ^{3}He events can be explained by this spallation process, then similar amount of ^{3}T should be ob-

Table 1. Coefficients of $H(^4He, D)^3He$ cross-section. The a is cross-section measured in mb.

cos Θ	a(mb/sr)	b	cos Θ	a(mb/sr)	b
1.0	0.52	-4.0	0.85	0.11	-3.9
0.95	0.41	-4.1	0.80	0.10	-4.0
0.90	0.12	-3.8	0.75	0.10	-4.2

served by the AMS above the cutoff. However, the efficiency of transportation may be different due to different rigidity, ^{3}He below the cutoff and ^{3}T above the cutoff.

3 Pick-up Reaction: p (^{4}He, d) ^{3}He

In this reaction, incident proton gets absorbed in the target ^{4}He to form a compound nucleus, which decays through the channel (d + ^{3}He). This reaction had been used to interpret the ^{3}He in radiation belts. We made use of the cross-section data given in Selesnick and Mewalt (1996). ^{3}He has the highest energy in the laboratory system when it is emitted in the forward direction in the center of mass system (CM). From the kinematics of this reaction, one expects the production of ^{3}He to be peaked both in the forward and backward direction in the CM. In reality, the forward peak is small, especially at higher projectile energies, due to the lesser probability for a bound ^{3}He in the forward direction. The cross-section for the production of ^{3}He per unit solid angle can be parameterized in the CM for a proton of kinetic energy $\mathrm{E'_p} > 100\mathrm{MeV}$ as,

$$d\sigma(E^*) = a(E'_p/100MeV)^b \tag{2}$$

Here, E^* is the total energy of ^{3}He in the CM for a given value of Θ^*. This differential cross-section is over a small energy interval $\Delta\mathrm{E}^* = \mathrm{E}_2^* - \mathrm{E}_1^*$, where E_1^* and E_2^* are the energies of ^{3}He emitted at angles Θ_1^* and Θ_2^*. The solid angle $d\Omega^*$ corresponding to $\Delta\mathrm{E}^*$ is $2\pi\Delta\ \cos\Theta^*$. The fitted parameters a & b for the above cross-sections for different CM angles of relevance are given in the table below. Θ^* is the angle between ^{3}He and the incident proton in the CM, ie. between $\boldsymbol{P^*_{^3He}}$ and $\boldsymbol{P}$, the total lab. momentum of the reaction. The energy spectrum of ^{3}He produced by this reaction can be evaluated from the integral,

$$J_{^3He}(E'_{^3He}) = \int \frac{J_p(E'_p)\sigma(E)dE'_p}{\Delta E'_{^3He}} \int n_{^4He}(h)dh \tag{3}$$

$\mathrm{dJ_p(E'_p)}$ is the differential energy spectrum of interacting protons; and n is the number density of ^{4}He at an altitude h in the atmosphere. Here, $\mathrm{E'_{^3He}}$ is expressed in kinetic energy per nucleon. To evaluate Eq.(3), one needs to obtain the cross-section in the lab. system from Eq. (1) using kinematics as $\mathrm{d}\sigma(\mathrm{E}) = \mathrm{d}\sigma(\mathrm{E}^*)\mathrm{d}\Omega^*/\mathrm{d}\Omega$.

3.1 Primary proton interaction with ambient helium

The protons in radiation belts are mostly below 1GeV, which cannot produce ^{3}He at 0.1 to 1.2 GeV/n, the proton energy must be in 0.35-4.5GeV in the lab. frame. At this energy, the proton flux in radiation belts is unknown and the primary cosmic proton fluxes (Alcaraz et al. , 2000) are used to estimate the possible phase space of rigidity and latitude. Using a similar simulation program as described in Sec.2.1, (by replacing the primary helium flux with the primary proton flux and using $10^{10}\mathrm{cm}^3$ for mean ^{4}He number density.) we can estimate the efficiency of ^{3}He production.

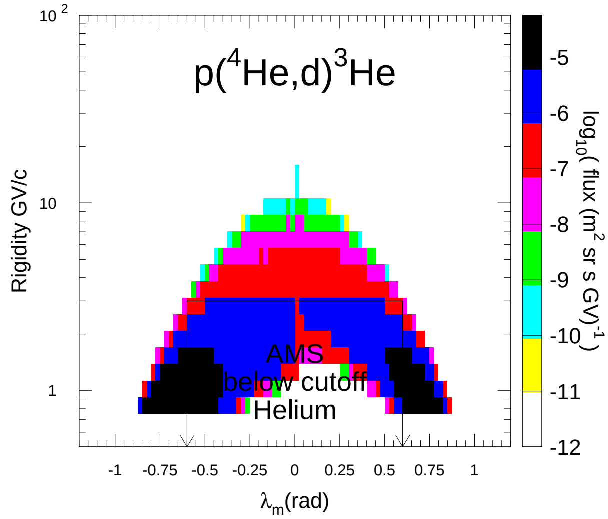

Fig. 2. The distribution of ^{3}He produced by $H(^4He, D)^3He$.

The results are shown in Fig. 2. Although ^{3}He could be produced in low latitude and similar rigidity ranges as the AMS measurements, there are some serious difficulties. First, the expected absolute intensity is too small. These below cutoff helium events are in the loss cone, they are constantly produced and absorbed. The ambient helium density is too low to produce ^{3}He flux comparable to that measured by the AMS.

The ^{3}He spectrum shown in Fig. **??** is very steep compared with that observed one. At E < 0.45GeV/n, the primary cosmic ray flux is around the top of the spectrum, the secondary ^{3}He spectrum reflects the E^{-4} of cross-section. Although it may seem that the spectrum is consistent with the AMS results, the low energy ^{3}He exists in high latitude region $|\lambda_m| > 0.5$, unlike the AMS result, which show that ^{3}He exists in $|\lambda_m| < 0.6$. At E > 0.45GeV/n, the spectrum is too steep to fit the AMS measurements. This is expected because the cross-section to produce ^{3}He has a power law with a spectral index of about -4, which makes the expected spectrum to be steeper by a power -3 compared with the input spectrum of protons.

Note that only the two body final state is considered in this simulation. It is reasonable to expect that the three body final state in which ^{3}He, p and n are produced. This process is more probable at high energies than the two body final state.

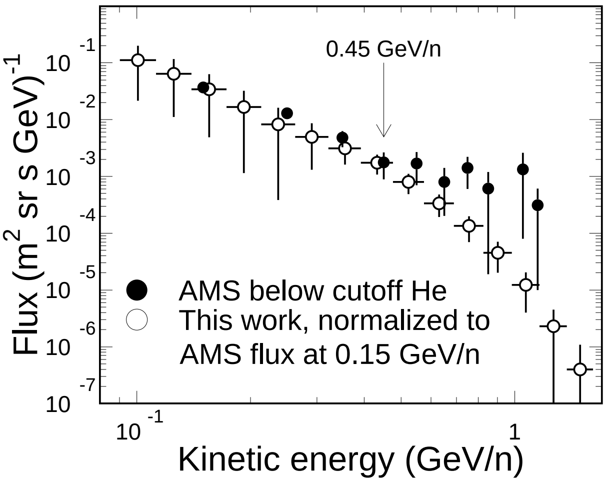

Fig. 3. The ^{3}He spectrum produced by $\mathrm{H}(^4\mathrm{He},\mathrm{D})^3$He is normalized to the same value as the AMS ^{3}He spectrum at 0.15 GeV/n.

However, there no cross-section is availabile to be incorporated in the calculations.

3.2 Secondary proton interacting with atmospheric nuclei

From the kinematics of this reaction, one can show that for producing ^{3}He over the energy domain from 0.1 to 1.2 GeV/n, as observed by the AMS, the interacting protons should have kinetic energies from 0.3 to 4 GeV. Even at about $|\lambda_m|$ = 0.6, the primary cosmic ray protons hardly reach the upper atmosphere except at energies close to 4 GeV. Therefore, one needs to rely on the secondary proton spectrum observed by the AMS (Alcaraz et al. , 2000) as the projectiles. This spectrum below 4 GeV is steeper than the corresponding primary spectrum, which becomes flatter due to solar modulation, and has a power index close to that of the primary protons at higher energy. This process has some advantages. (1) Albedo protons exist all over the Earth, constantly produced by cosmic rays. They also have similar latitude distribution. (2) Energy of albedo proton ranges from 0.1 to 6 Gev. (3)p + O produce more ^{3}He than ^{4}He (Komarov , 1974). Total cross-sections of ^{3}He and ^{4}He stay approximately constant at 3-10 GeV. (Cucinota et al. , 1996); however, differential cross-section is not available.

4 Disintegration of Air Nuclei

Laboratory experiments with low energy proton projectiles below 100 MeV (Wu et al. , 1979; Bertrand and Peelle , 1973) show that compound nucleus is formed in an excited state, which disintegrates into fragments. The energy spectrum of these fragments has the typical evaporation spectrum with a peak and extends to high energies with an exponential tail. The exponential part of the spectrum is softer with increase in fragment mass. This is due to the lower probability at higher momenta of finding a larger number of nucleons of almost the same momentum in the phase space. Because of this reason, one expects the ^{3}He/^{4}He should be larger except at low energies closer to the binding energy for ^{4}He, where it is expected that this ratio becomes much smaller. The experiments also show that the high energy continuum shows a strong angular dependence in the forward direction. Since the available energy increases with heavier projectiles, leading to larger available momentum for the fragments, interaction of heavier cosmic ray nuclei can also contribute to this process. In principle, if the cross-section for the production of ^{3}He and ^{4}He by this process as a function of projectile energy is known, the contribution from this process can be estimated.

If the disintegration of air nuclei during high energy collision produces ^{3}He, then the projectiles should be the observed secondary protons, which have the same latitude dependence. Since the ^{3}He is produced along the horizon, one can in principle estimate the probability of these particles to be observed by the AMS as a function of both energy per nucleon and latitude. Using this probability, one can obtain the shape of the emission spectrum, which will throw light on the exact process that is responsible for the high energy ^{3}He observed below the geomagnetic cut-off.

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